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(54) **EXTRUDED DEPOSITION OF FIBER REINFORCED POLYMERS**

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CPC *B29C 48/154* (2019.02); *B29C 48/022* (2019.02); *B29C 48/18* (2019.02); *B29C 48/285* (2019.02); *B29C 48/503* (2019.02); *B29C 48/865* (2019.02); *B29C 64/118* (2017.08); *B29C 70/24* (2013.01); *B33Y 10/00* (2014.12); *B33Y 30/00* (2014.12); *B29B 15/122* (2013.01); *B29L 2031/3076* (2013.01)

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(58) **Field of Classification Search**
None
See application file for complete search history.

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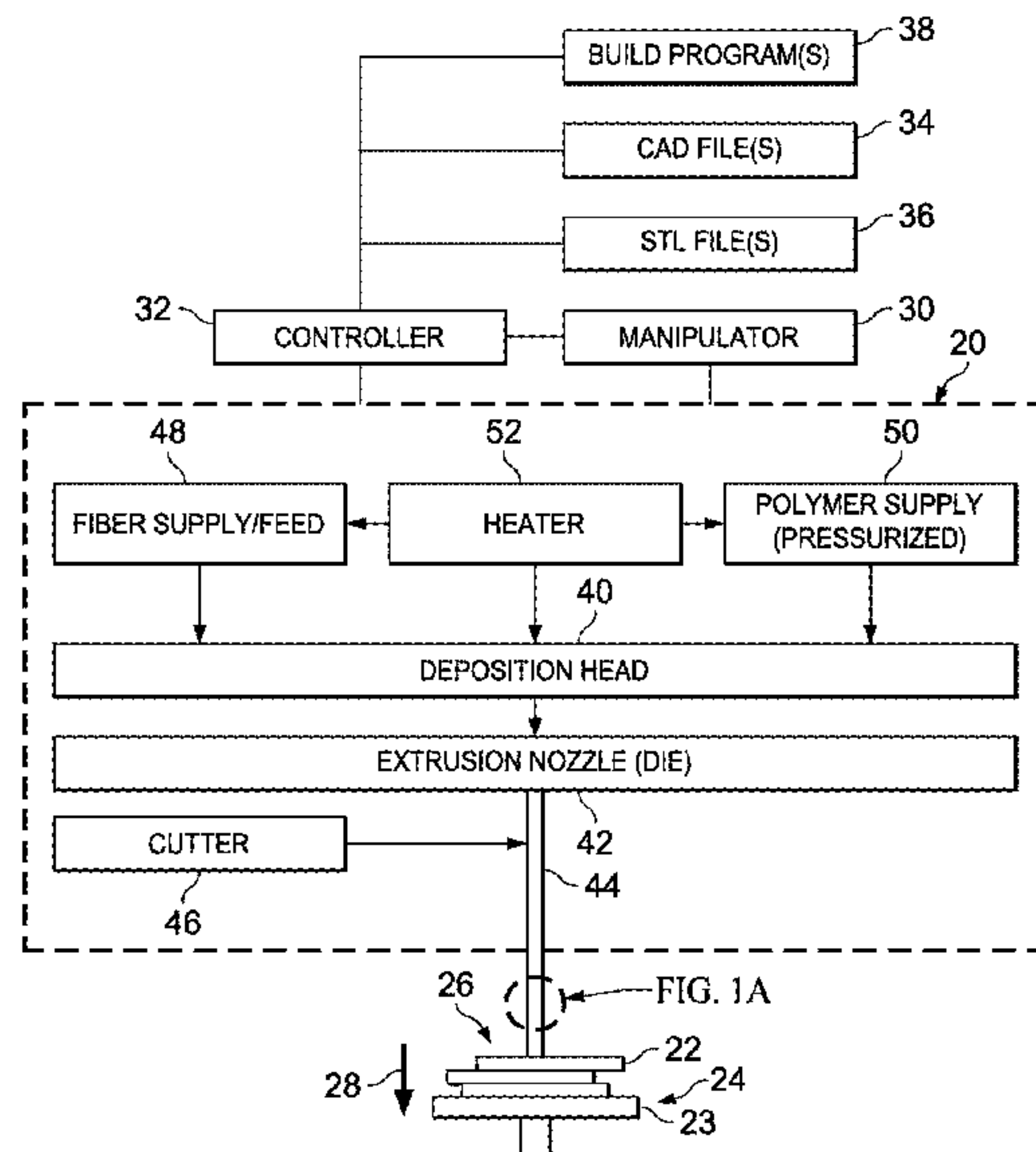
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(57) **ABSTRACT**
A fiber reinforced polymer part is fabricated by rastering a deposition head over a substrate, and additively forming part features by extruding a polymer having an entrained continuous reinforcement from the deposition head onto a substrate.

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20 Claims, 4 Drawing Sheets



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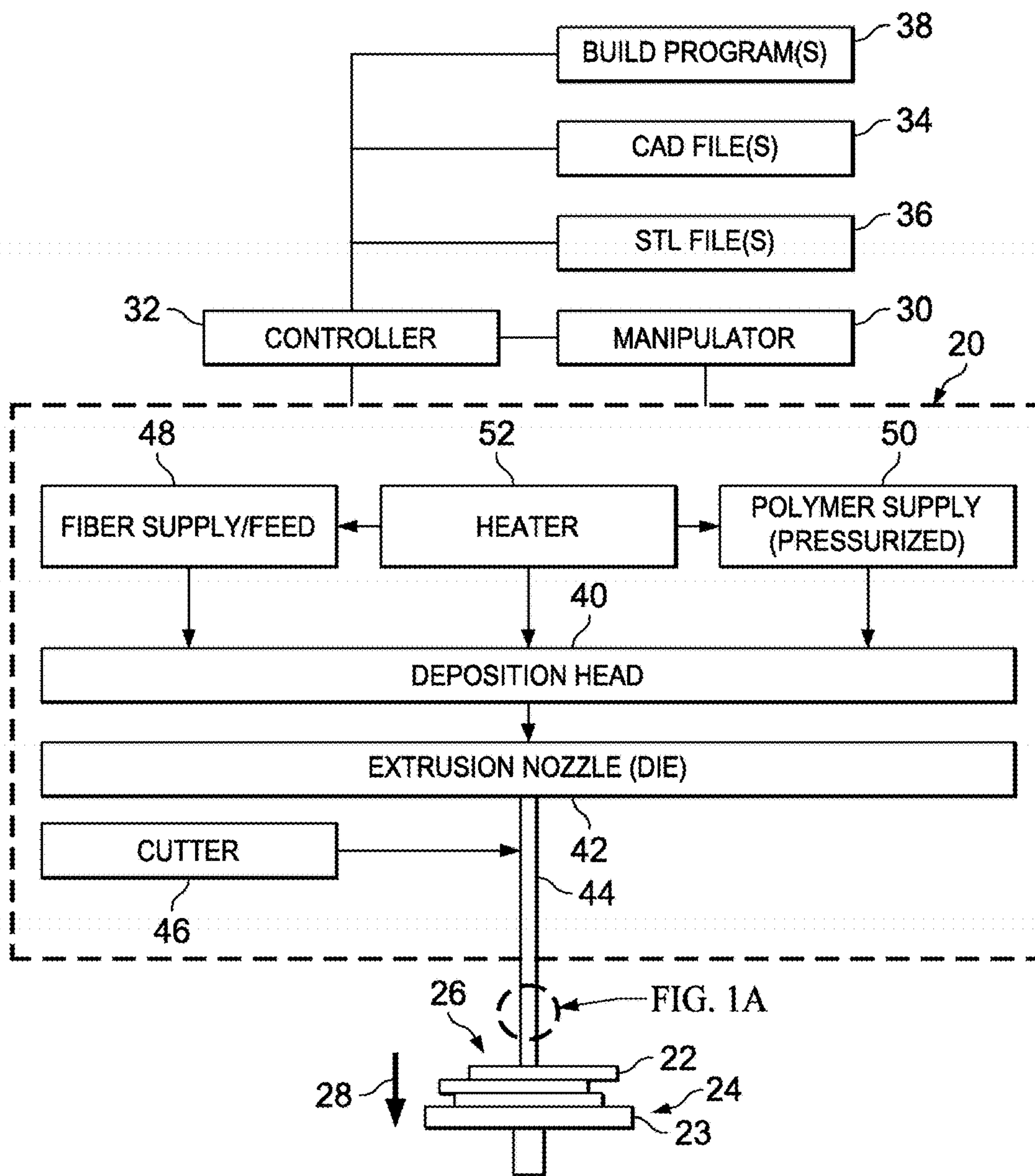


FIG. 1

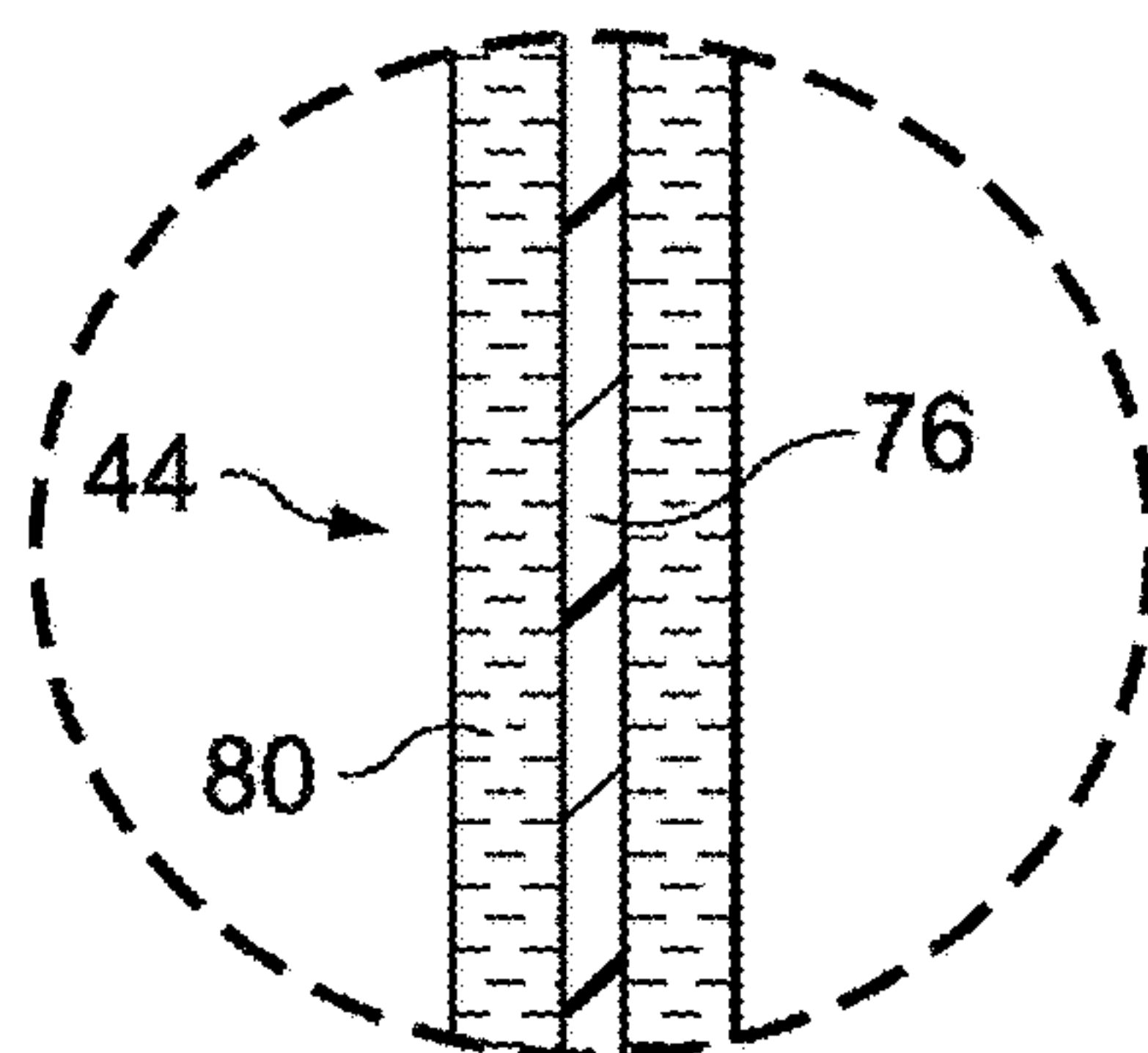


FIG. 1A

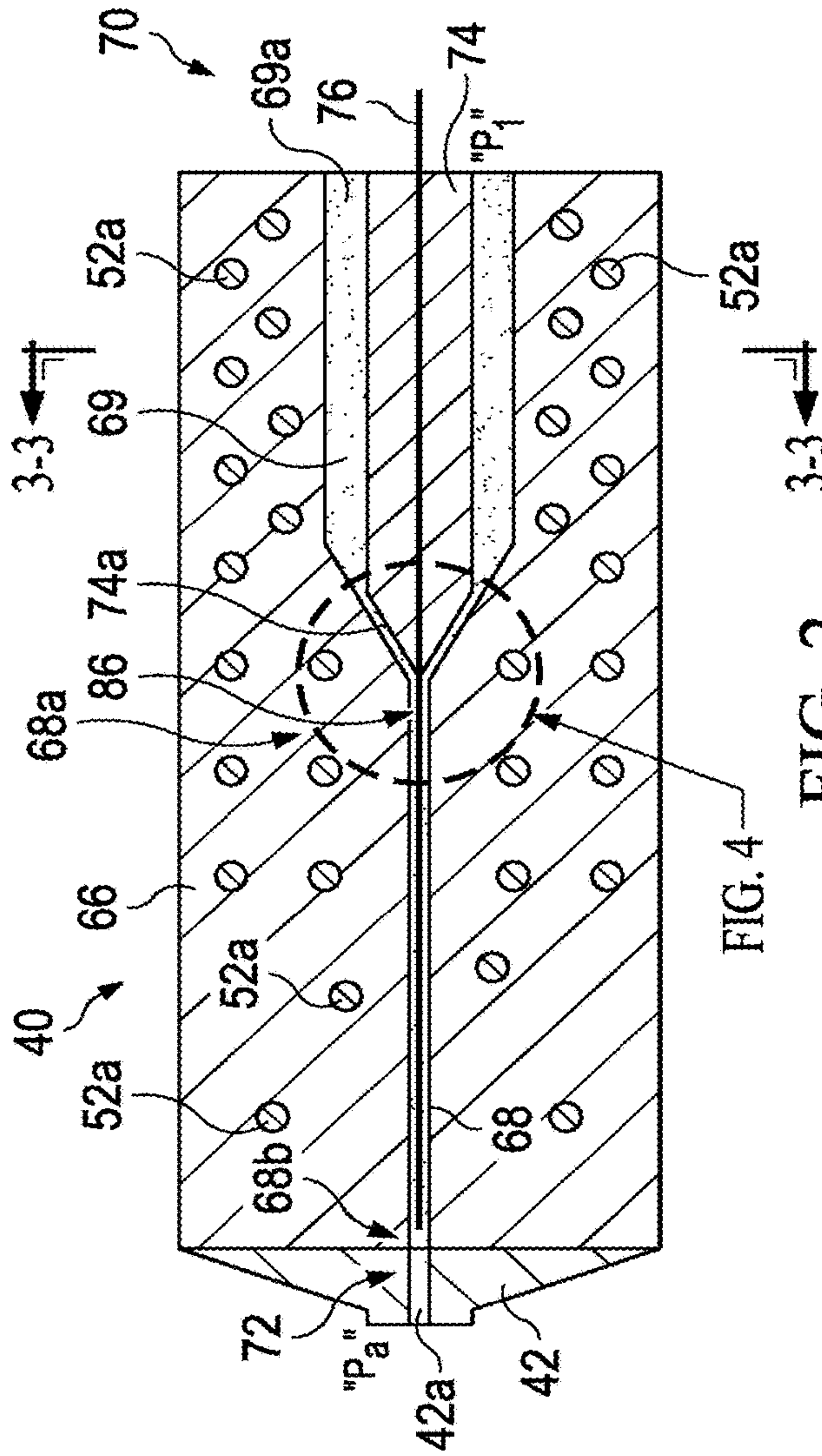


FIG. 2

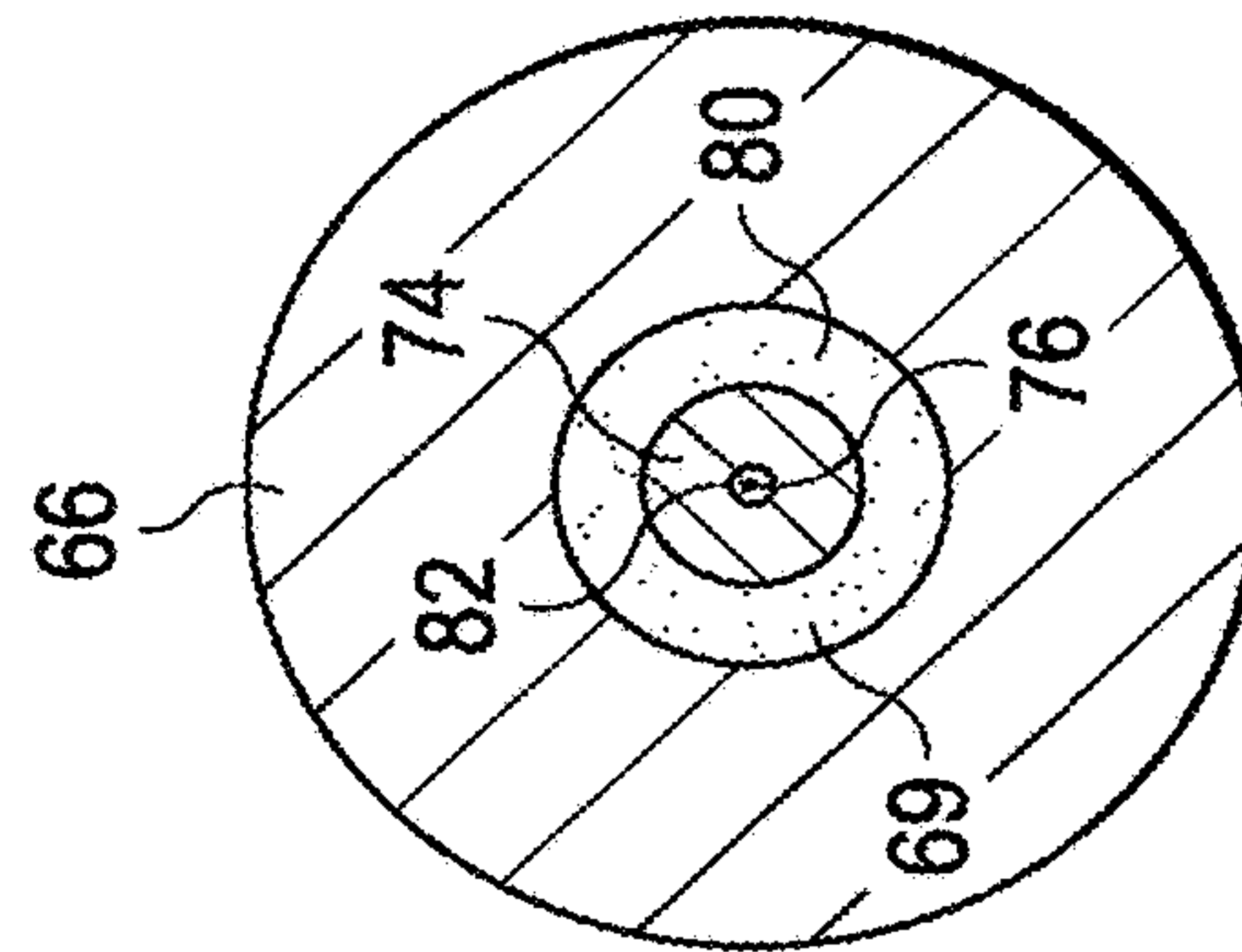


FIG. 3

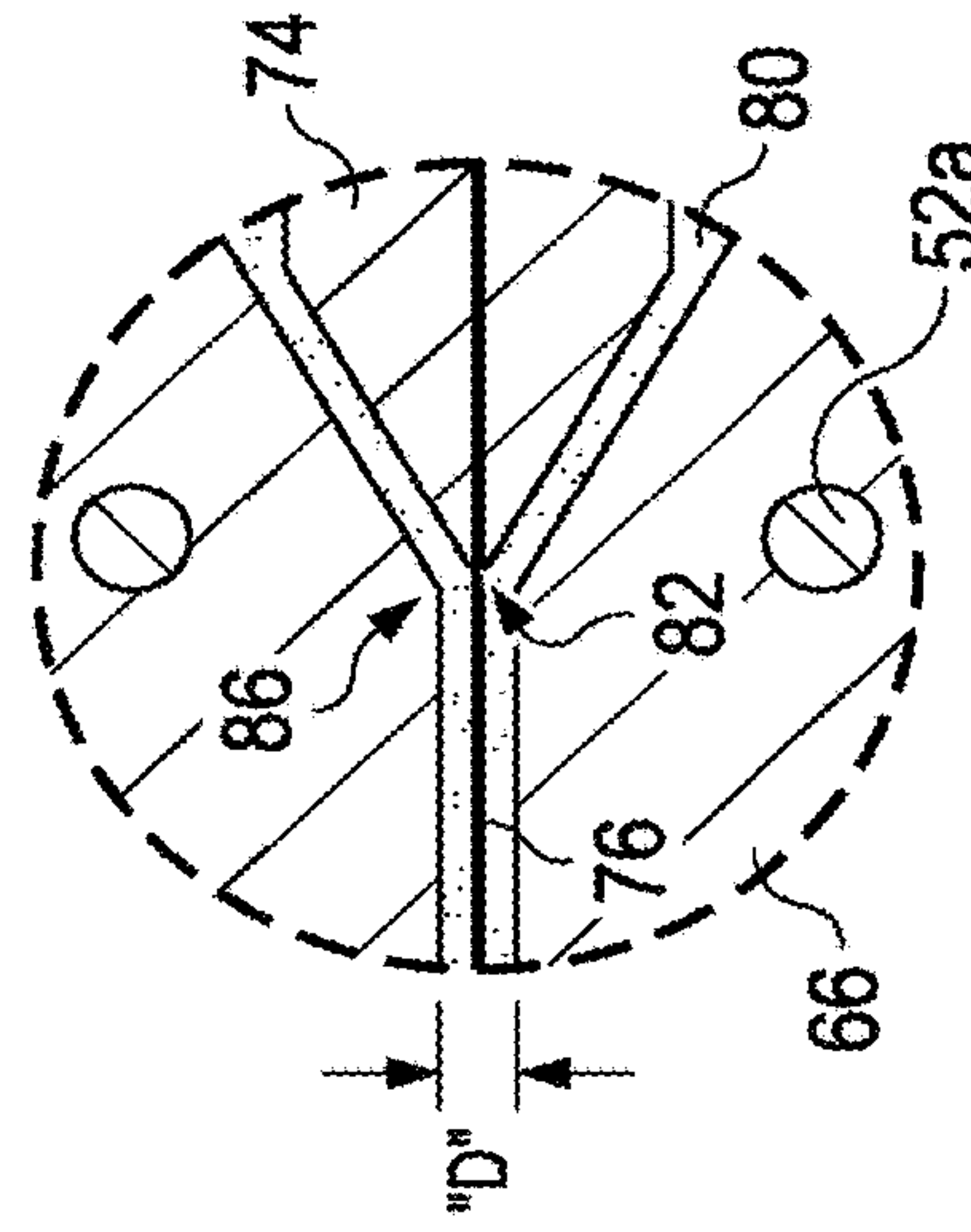


FIG. 4

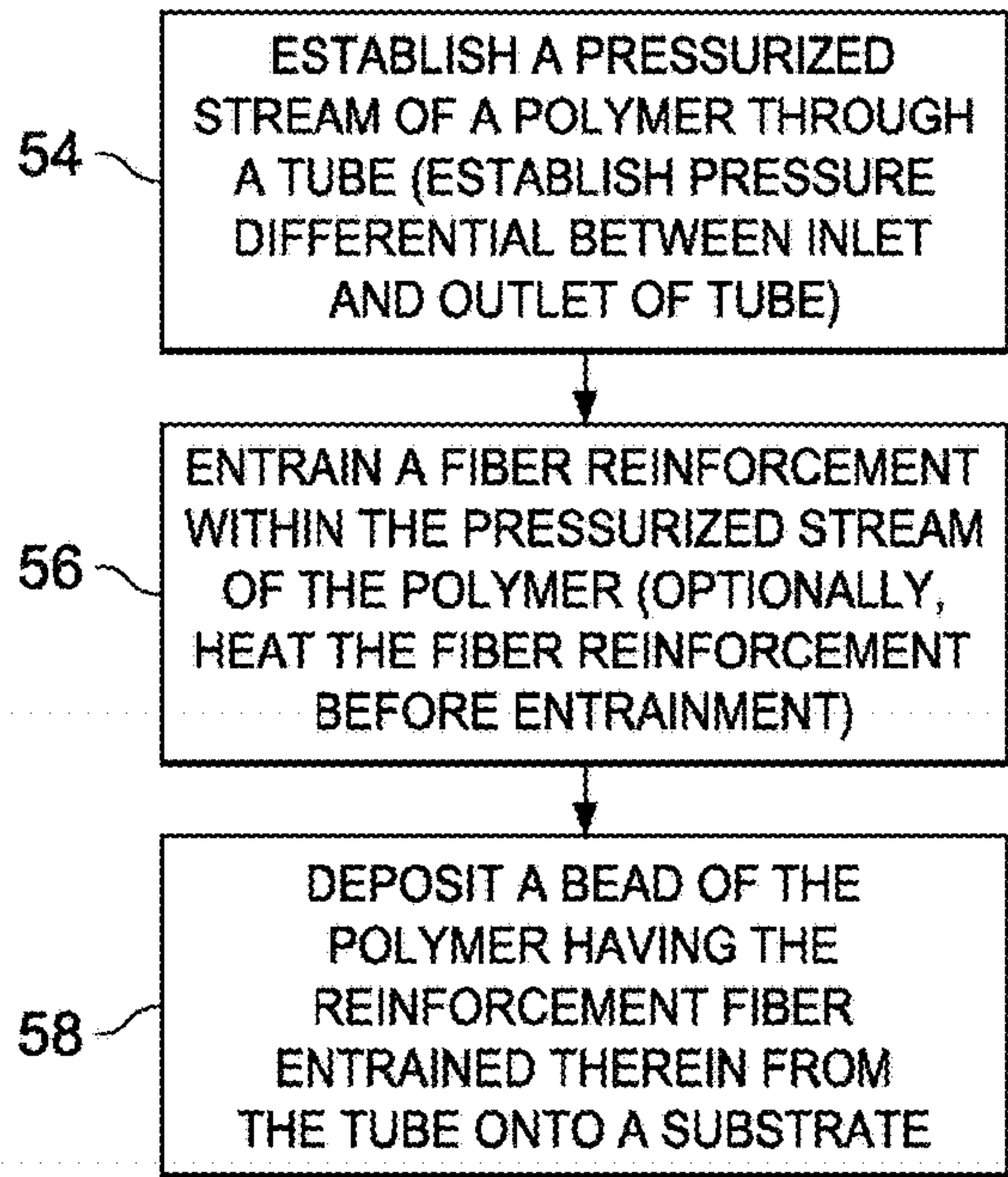


FIG. 5

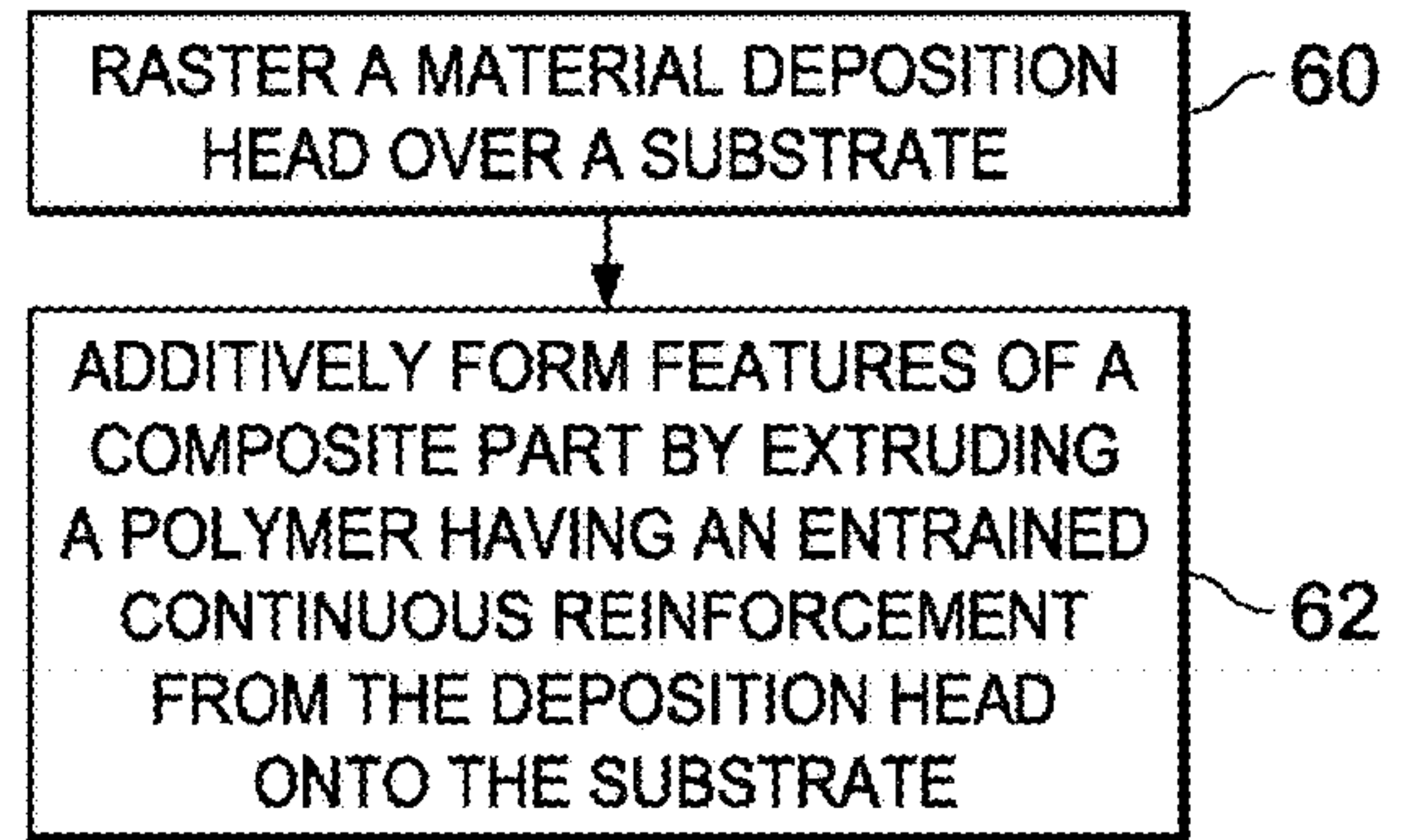


FIG. 6

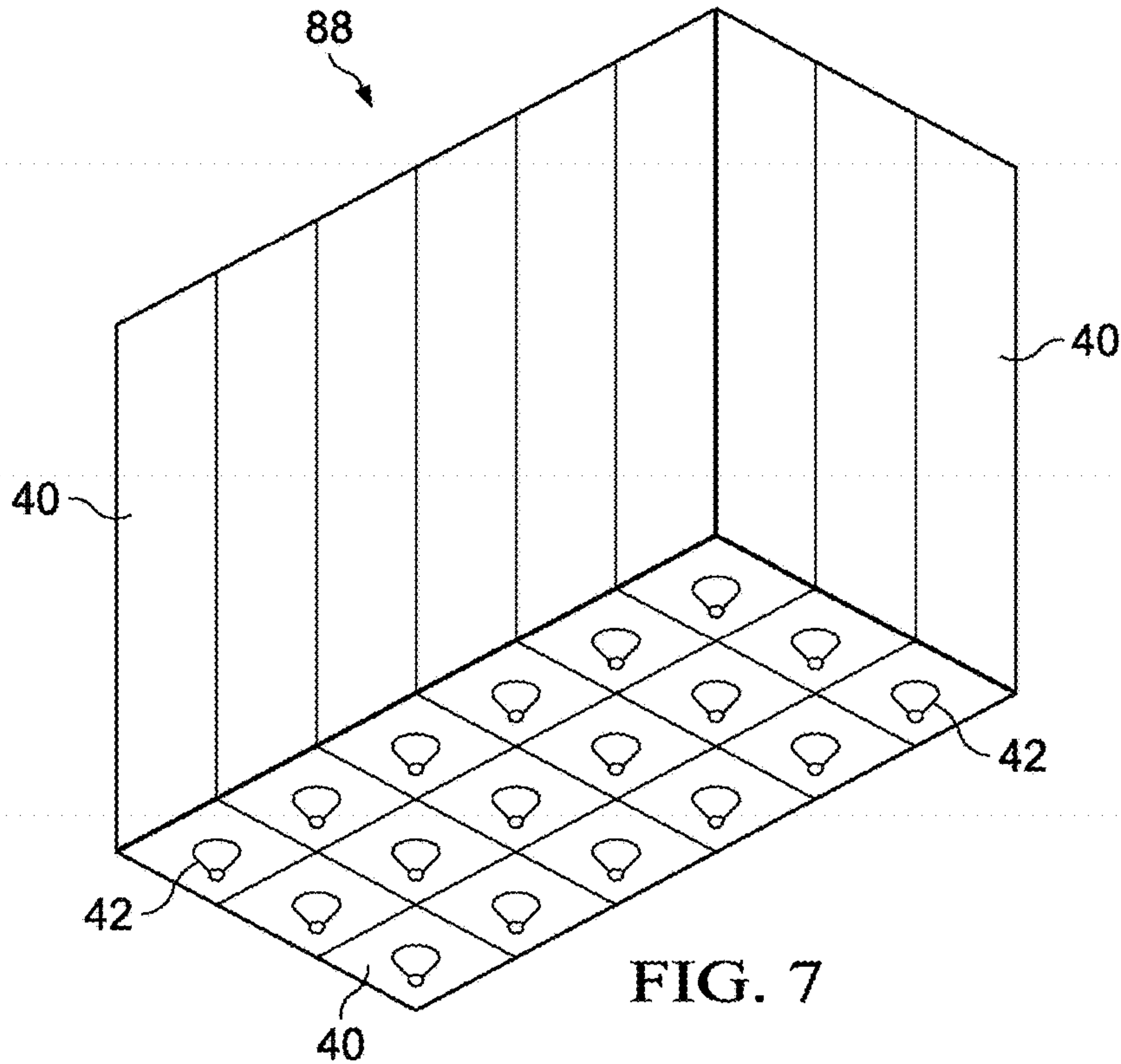


FIG. 7

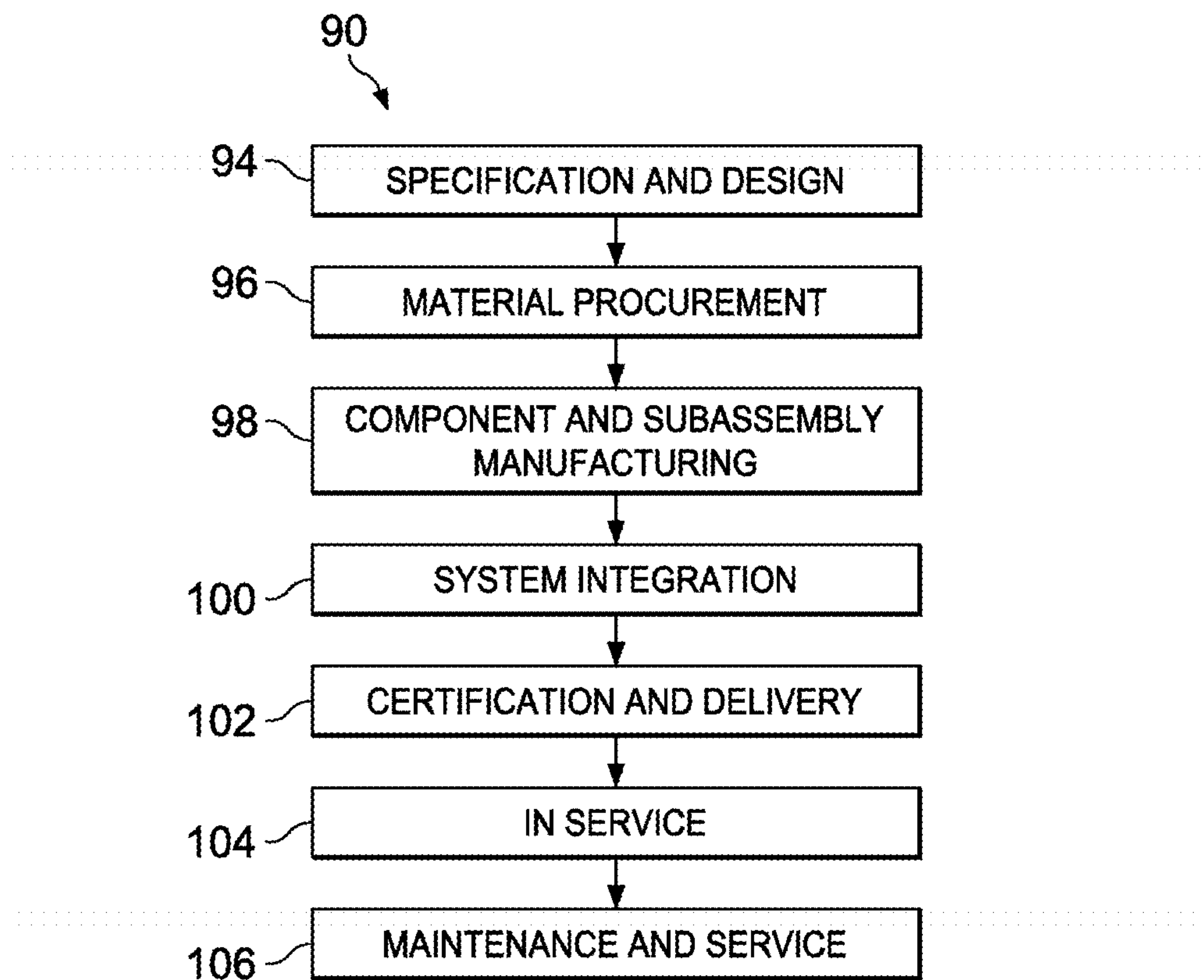


FIG. 8

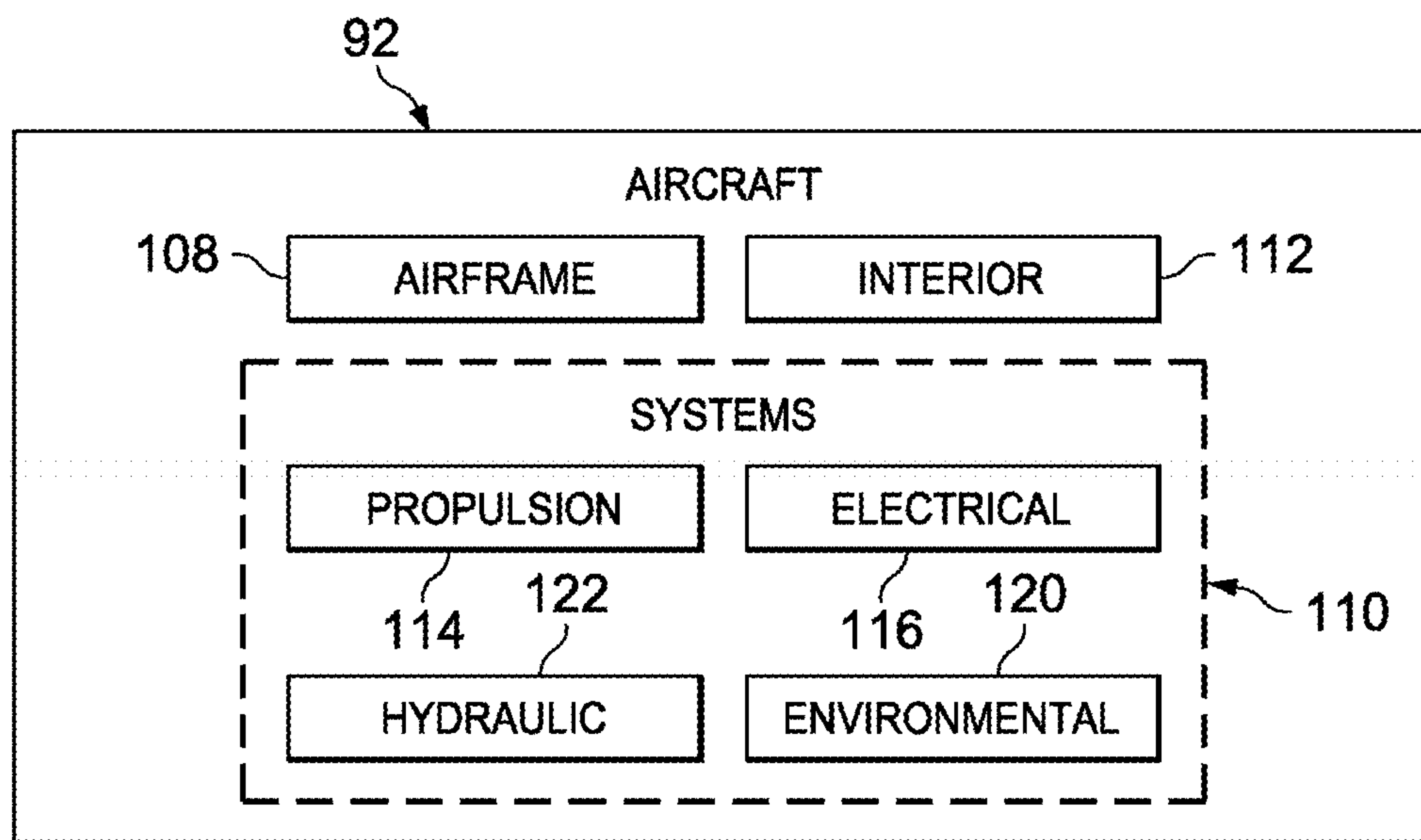


FIG. 9

EXTRUDED DEPOSITION OF FIBER REINFORCED POLYMERS

This application is a divisional application of U.S. application Ser. No. 14/489,972, filed Sep. 18, 2014, now U.S. Pat. No. 9,931,778.

BACKGROUND INFORMATION

1. Field

The present disclosure generally relates to additive manufacturing techniques, and deals more particularly with a method and apparatus for deposition of fiber reinforced polymers, such as thermoplastic polymers.

2. Background

Additive manufacturing is a process in which physical parts are produced directly from a 3-D (three dimensional) CAD (computer aided design) file. In one type of additive manufacturing known as fused deposition modeling (FDM®) and sometimes referred to as 3-D printing, a part is produced by extruding small beads of thermoplastic polymer material to form layers of the material that solidifies after being extruded from a nozzle. The extrusion nozzle may be moved along a toolpath or “rastered” by a numerically controlled mechanism to build the part from the bottom up on a build platform, one layer at a time.

Parts produced by known additive manufacturing processes, such as FDM®, may not be suitable for use in some applications requiring high structural performance, such as in the aerospace industry. In order to achieve higher structural performance, thermoplastic parts used in these applications typically require the use of an embedded reinforcement such as discontinuous or continuous fibers. However, the integration of a continuous fiber reinforcement into an extruded thermoplastic polymer during fused deposition modeling has not been heretofore practical.

It is known to introduce discontinuous (e.g. “chopped”) reinforcing fibers into an extruded polymer. For example, a process known as PUSHTRUSION® has been developed for molding reinforced polymer composites using a direct, in-line compounding and molding process, in which the mold charge comprises extruded polymer pellets or strands reinforced with discontinuous fibers. However, the PUSHTRUSION® process utilizes large and heavy industrial equipment meant to provide discontinuous fiber reinforced polymer strands or pellets for molding, and is not suitable for use in additive manufacturing processes such as FDM.

Accordingly, there is a need for an additive manufacturing process such as FDM that allows integration of a reinforcement into a bead of polymer deposited in layers to form features of a part. There is also a need for an end effector to carry out the process described above which allows entrainment of a continuous reinforcement into a liquified polymer as the end effector builds features of the part.

SUMMARY

The disclosed embodiments provide a method and apparatus for fabricating reinforced polymer parts using an additive manufacturing technique. The reinforcement may be continuous and is integrated into a molten bead of the polymer as the polymer is being deposited in layers to form features of the part, similar to fused deposition modeling. The embodiments permit fabrication of parts having higher

structural performance requirements. High resolution deposition of continuously reinforced polymers is made possible.

According to one disclosed embodiment, a deposition fabrication method is provided. The method comprises establishing a pressurized stream of a molten polymer through a tube, entraining a fiber reinforcement within the pressurized stream, and depositing a bead of the polymer and the fiber reinforcement from the tube onto a substrate. The fiber reinforcement is entrained by feeding it into the tube. The fiber reinforcement may comprise a filament, a tow, a roving or a yarn. The fiber reinforcement may be entrained by feeding one of a dry fiber reinforcement and a pre-impregnated fiber reinforcement into the tube. The fiber reinforcement may be heated. In one variation, a plurality of discontinuous fiber reinforcements may be coupled together into a chain, and the chain may be entrained by drawing it into the pressurized stream. The method may also include encapsulating the fiber reinforcement in a polymer having a melt temperature that is higher than the melt temperature of the polymer in the pressurized stream. A desired polymer viscosity may be maintained by applying a varying amount of heat to the tube along its length. Optionally, the method may further include depositing a bead of polymer onto the substrate wherein the polymer is devoid of the fiber reinforcement. The pressurized stream is established by injecting the polymer under pressure into the tube. Injecting the polymer under pressure into the tube includes establishing a pressure differential between an upstream end and a downstream end of the tube. The method may also include drawing the fiber reinforcement through the tube along with the polymer using the pressurized stream and/or by capillary action. The fiber reinforcement may be entrained by introducing it into an upstream end of the tube. The polymer is introduced into the tube annularly around the fiber reinforcement

According to another embodiment, a method is provided of fabricating a composite part. A deposition head is rastered over a substrate. Features of the part are additively formed by extruding a polymer having a reinforcement from the deposition head onto a substrate. The method may include entraining a discontinuous reinforcement in the polymer, or alternatively, entraining a continuous reinforcement in the polymer. In one variation, features may be extruded that are devoid of the reinforcement. The extrusion includes introducing the polymer and the reinforcement into an upstream end of a tube, forcing the polymer to flow through the tube to a downstream end of the tube, and drawing the reinforcement through the tube to the downstream end of the tube by using the flow of polymer through the tube to drag the reinforcement along with the polymer flow. The method may also include using capillary action to assist in drawing the reinforcement through the tube. The polymer is introduced by injecting the polymer under pressure around the reinforcement. The extrusion includes forcing the polymer and the entrained reinforcement through a die. The method may also include cutting the polymer and the reinforcement during rastering of the deposition head.

According to still another embodiment, an end effector is provided for performing deposition of a fiber reinforced polymer. The end effector includes a supply of a continuous fiber reinforcement, and a supply of a flowable polymer. A deposition head is provided having a polymer inlet and a material supply end configured to receive a supply of a continuous fiber reinforcement. The deposition head also includes a deposition end configured to deposit a bead of the polymer having the continuous fiber reinforcement entrained therein. The end effector may further comprise a

heater for heating the entrainment barrel, including at least one heating coil having a plurality of coil turns that vary in number along a length of the entrainment barrel. The deposition head includes an entrainment barrel configured to entrain the continuous fiber reinforcement. The entrainment barrel includes a convergence region in which the continuous fiber reinforcement and the flowable polymer converge. The entrainment barrel may also include an extrusion die coupled with the deposition end. The entrainment barrel may further include a capillary tube coupled with the convergence region and configured to entrain the continuous fiber reinforcement in the polymer.

The features, functions, and advantages can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

FIG. 1 is an illustration of an overall block diagram of an apparatus for fabricating a fiber reinforced part using an additive manufacturing technique;

FIG. 1A is an illustration of the area designated as "FIG. 1A" in FIG. 1, parts of an extruded bead being broken away to reveal a fiber reinforcement entrained in polymer;

FIG. 2 is an illustration of a cross-sectional view of a deposition head which forms part of the apparatus shown in FIG. 1;

FIG. 3 is an illustration of a sectional view taken along the line 3-3 in FIG. 2;

FIG. 4 is an illustration of an enlarged view of the section designated as "FIG. 4" in FIG. 2;

FIG. 5 is an illustration of a flow diagram of one embodiment of a deposition method;

FIG. 6 is an illustration of a flow diagram of a method of fabricating a composite part;

FIG. 7 is an illustration of a bottom, perspective view of a deposition head array for deposition of a fiber reinforced polymer;

FIG. 8 is an illustration of a flow diagram of an aircraft production and service methodology; and

FIG. 9 is an illustration of a block diagram of an aircraft.

DETAILED DESCRIPTION

Referring to FIG. 1, the disclosed embodiments comprise an end effector 20 that may be rastered through three dimensional space over a substrate 23 such as a platform 24 by any suitable manipulator 30. The manipulator 30 may comprise, for example and without limitation, a numerically controlled gantry mechanism (not shown), and an articulated robotic arm (not shown) or a similar mechanism. Both the end effector 20 and the manipulator 30 are operated by the combination of a controller 32 and build programs 38 or similar software. The controller 32 may comprise, without limitation, a programmed special-purpose or general purpose computer, such as a PC (personal computer) or a PLC (programmable logic controller).

The end effector 20 builds a three dimensional, fiber reinforced, polymer part 26, layer 22 by layer 22 on the platform 24 which moves down 28 as each reinforced polymer layer 22 is completed. The polymer part 26, sometimes referred to herein as a composite part 26, is defined by one or more CAD (computer aided design) files 34 which are converted to STL (stereolithography) format files 36 defining the surfaces of the part 26. Using the STL files 36, and one or more build programs 38, the controller 32 controls the operation of the end effector 20 and the manipulator 30. The manipulator 30 rasters the end effector 20 over the platform 24 to deposit molten beads 44 of soft, fiber reinforced polymer that subsequently solidify. As shown in FIG. 1A, each of the molten beads 44 comprises an extruded polymer 80 having a continuous fiber reinforcement 76 entrained therein. As the reinforced polymer solidifies, the layers 22 fuse together to form the various features of the fiber reinforced composite part 26.

The end effector 20 includes a deposition head 40 that may be provided with an extrusion nozzle or die 42 through which a fiber reinforced molten bead 44 of reinforced polymer is deposited onto the platform 24, or onto an underlying layer 22. As mentioned above, the bead 44 includes a fiber reinforcement 76 (FIGS. 1, 2, 3 and 4) that is entrained in the extruded polymer 80 as the beads 44 are extruded to form the layers 22 which then solidify and fuse together. The extrusion nozzle 42 may have a nozzle opening 42a (FIG. 2) for extruding a polymer bead 44 having the entrained fiber reinforcement 76. The nozzle opening 42a may have desired cross-sectional shape such as, without limitation, a circular, square, elliptical, ribbon or rectangular cross-sectional shape.

The end effector 20 further comprises a fiber supply and feed 48, a pressurized polymer supply 50 and one or more suitable heaters 52. The polymer supply 50 may include one or more control valves and pressure regulators (not shown) as may be required for controlling the flow and pressure of polymer that is supplied to the deposition head 40. The heater 52 heats the polymer until it liquefies and becomes flowable, and also provides heat to the deposition head 40 to maintain the polymer desired viscosity until the polymer 80 and entrained fiber reinforcement 76 exit the extrusion nozzle 42. The desired polymer viscosity may depend on a variety of factors, including without limitation, the temperature to which the polymer is heated, the amount of heat absorption by the fiber reinforcement 76, the particular polymer 80 being used and its shear rate, the ability of the fiber reinforcement 76 to be wetted by the polymer 80, the desired rate of extrusion from the deposition head 40 and the rate at which the end effector 20 is rastered over the substrate 23. Generally, however, the polymer 80 should have a viscosity that is low enough to wet out the fiber reinforcement 76 and be extruded from the deposition head 40.

Optionally, the heater 52 may be used to heat the fiber reinforcement 76 before and/or as it is being fed into the deposition head 40 and becomes entrained in the polymer 80. The end effector 20 may also include a suitable cutter 46 which cuts the fiber reinforced polymer bead 44 after a layer 22 has been deposited. The cutter 46 may comprise, for example and without limitation, a laser cutter, an ultrasonic knife or a mechanical cutter such as a guillotine blade (all not shown) that cuts through both the polymer 80 and the entrained fiber reinforcement 76.

The polymer 80 supplied to the deposition head may be any phase changeable polymer that reduces in viscosity when heated to at least its glass transition temperature, and then solidifies and hardens when cooled. For example, and

without limitation, the polymer **80** drawn into the deposition head **40** from the polymer supply **50** may comprise any suitable amorphous or crystalline thermoplastic polymer, thermoset or a thermoplastic co-polymer.

The fiber reinforcement **76** that is entrained in the polymer **80** may comprise one or more fiber filaments, tows, rovings, or yarns that are compatible with the polymer **80**, such as carbon, glass, ceramic or metal fibers, or combination of such fibers. The fiber reinforcement **76** may be in the form of, without limitation, one or more tows, rovings or yarns, each comprising a multiplicity of individual filaments. In some embodiments, for example, the reinforcement **76** may comprise a single tow, roving or yarn comprising a linear weight between 2 and 16 tex, wherein a "tex" is the mass in grams of 1,000 meters of a thread of the tow, roving or yarn. The fiber reinforcement **76** may be a dry fiber reinforcement or may be pre-impregnated fiber reinforcement.

The tow, roving or yarn may comprise dry filaments, however in some embodiments, the tow may be pre-impregnated with a polymer that is the same as or different from the polymer **80** drawn from the polymer supply **50**. It may also be possible to form a reinforcement strand by encapsulating a tow, roving or yarn in a first polymer that has a relatively high melt temperature, and then feed the encapsulated tow through the deposition head **40** where it is entrained within a second polymer **80** that has a melt temperature that is lower than that of the first polymer. In other embodiments, the fiber reinforcement **76** may comprise discontinuous fiber reinforcements (e.g. chopped fibers) that may or may not be aligned and are coupled together, as by a binder, into a chain (not shown) that can be drawn or "pulled" through the deposition head **40** by a flowing stream of the polymer **80** in which the chain of discontinuous fiber reinforcements **76** is entrained.

Attention is now directed to FIGS. **2**, **3** and **4** which illustrate details of the deposition head **40** which comprises the forming part of the end effector **20**. The deposition head **40** includes an elongate entrainment barrel **66** having a material supply end **70**, and a material deposition end **72** from which a molten bead **44** (FIG. **1**) of fiber reinforced polymer is extruded and deposited, as previously explained. The entrainment barrel **66** includes an internal capillary tube **68** having first upstream end **68a**, and a second, downstream end **68b** opposite the upstream end **68a**. The capillary tube **68** extends longitudinally from the material deposition end **72** of the entrainment barrel **66** to a convergence region **86** where the fiber reinforcement **76** is introduced into and converges with a flowing stream of the polymer **80** that is introduced into the entrainment barrel **66** upstream of the convergence region **86**.

When the fiber reinforcement **76** is introduced into the flowing stream of the polymer **80**, viscous interaction between the fiber reinforcement **76** and the polymer **80** pulls the fiber reinforcement **76** into the upstream end **68a** of, and then through the capillary tube **68**. Upon entering the convergence region **86**, the fiber reinforcement **76** becomes entrained in the flowing stream of polymer **80** and is carried along with the polymer **80** through the capillary tube **68** to the material deposition end **72** of the entrainment barrel **66** where the polymer **80** and the entrained fiber reinforcement **76** are extruded together as a bead **44**.

The downstream end **68b** of the capillary tube **68** may be coupled with an extrusion die **42** in order to extrude a polymer bead **44** having a desired cross-sectional shape. In some applications, the extrusion die **42** may not be necessary. The capillary tube **68** has an inside diameter "D" that

will depend on a variety of factors, including the particular deposition application, the print resolution of the part **26** (FIG. **1**) being fabricated and the volume fraction of fiber reinforcement **76** that is desired. The volume fraction of the fiber reinforcement **76** contained in the polymer is a function of both the inside diameter "D" of the capillary tube **68**, and the number and diameter of the fibers that form the fiber reinforcement **76**. The length of the capillary tube **68** may also affect the amount of entrained polymer-to-fiber interaction that is needed to move the fiber reinforcement **76** through the capillary tube **68**.

The material supply end **70** of the entrainment barrel **66** is provided with a centrally located guide tube **74** into which the fiber reinforcement **76** may be longitudinally fed from the fiber supply and feed **48** (FIG. **1**). The downstream end **74a** of the guide tube **74** is tapered and includes a central opening **82** (FIGS. **3** and **4**) that is coaxially aligned with the capillary tube **68**. After being fed into the guide tube **74**, the fiber reinforcement **76** is guided through the opening **82**, in axial alignment with the capillary tube **68**, and enters the convergence region **86** where it converges with, is exposed to and becomes wetted by molten polymer that flows over the outside of guide tube **74** into the capillary tube **68**. As the fiber reinforcement **76** enters the convergence region **86**, it becomes entrained within the polymer **80** flowing through the convergence region **86** into the capillary tube **68**.

The material supply end **70** of the entrainment barrel **66** further includes an annular polymer passageway **69** surrounding the guide tube **74**. In one embodiment, flowable molten polymer **80** may be introduced into the annular polymer passageway **69** through a polymer inlet **69a** at the material supply end **70** (as illustrated), in a direction generally parallel to the direction in which the fiber reinforcement **76** is fed into the guide tube **74**. Alternatively, in another embodiment (not shown), the flowable molten polymer **80** may be cross-fed through the side of the entrainment barrel **66** into the passageway **69** in a direction that is transverse to the direction in which the fiber reinforcement **76** is fed into the guide tube **74**.

Polymer **80** is injected from the polymer supply **50** into the polymer inlet **69a** at a pressure " P_1 ", and flows into through the annular passageway **69**. The annular passageway **69** tapers and converges with the tapered end **74a** of the guide tube **74**, causing the flowing polymer **80** to flow past and over the fiber reinforcement **76** into the upstream end **68a** of the capillary tube **68**. The pressure " P_1 " is greater than atmospheric pressure " P_a " at the material deposition end **72** of the of the entrainment barrel **66**, consequently a pressure differential of $P_1 - P_a$ exists between the opposite ends **68a**, **68b** of the capillary tube **68**. This pressure differential assists in drawing and entraining the fiber reinforcement **76** into the flowing polymer **80**.

The heater **52** shown in FIG. **1** may include one or more electric heating coils **52a** that either surround or are embedded in the entrainment barrel **66** as shown in FIG. **2**. The electric heating coils **52a** provide the necessary heat to maintain the polymer **80** in a flowable state with a desired viscosity. It may be desirable to maintain the temperature of the entrainment barrel **66** at the material supply end **70** at a temperature that is greater than the temperature at the material deposition end **72** in order to assure adequate wetting of the fiber reinforcement **76** as it is initially drawn into the capillary tube **68**. In order to vary the amount of heat supplied to the polymer **80** as it travels along the length of the entrainment barrel **66** and thereby control the viscosity of the polymer **80**, the heating coils **52a** may have a greater number of coil turns at the material supply end **70** on the

entrainment barrel 66 compared to the number of coil turns at the material deposition end 72.

In use, one or more fiber reinforcements 76 are loosely fed into the guide tube 74 such that they are not placed in any substantial amount of compression, i.e. they are not forced into the guide tube 74, and consequently buckling of the fiber reinforcements 76 is avoided. As previously mentioned, the entrainment barrel 66 is heated to a temperature that maintains the polymer 80 flowable and assures substantially complete wetting of the fiber reinforcement 76. Polymer 80 under pressure P_1 is introduced into the polymer inlet 69a, filling the annular passageway 69, and establishing a flow of the polymer 80 through the convergence region 86 into the upstream end 68a of the capillary tube 68. The polymer pressure differential $P_1 - P_a$ established between the polymer inlet 69a and the material deposition end 72 maintains the flow of polymer 80 to the capillary tube 68. In other words, the polymer 80 seeks to equilibrate by flowing from the polymer inlet 69a at a relatively high pressure P_1 to the material deposition end 72 at relatively lower pressure P_a .

The flow of the polymer 80 through the convergence region 86 produced by the pressure differential $P_1 - P_a$ causes the polymer 80 to "grab" and draw the fiber reinforcement 76 along with the flowing polymer 80 into the upstream end 68a of the capillary tube 68 where it becomes entrained in the polymer 80. Additionally, the fiber reinforcement 76 is drawn through the capillary tube 68 by capillary action produced by intermolecular forces between the polymer 80 and the surrounding capillary tube 68. As the fiber reinforcement 76 is drawn into the capillary tube 68, fiber reinforcement 76 becomes entrained within the flowing polymer 80 and is extruded and then deposited along with the polymer 80 in a molten bead 44 (FIG. 1) to form successive layers 22 of the part 26 as the end effector 20 is rastered over the substrate 23.

When a layer 22 or other feature of the part 26 has been formed, the cutter 46 severs the bead 44, and the polymer supply 50 may be shut off until the end effector 20 is ready to deposit the next layer 22. Severing of the bead 44 results in severing of both the polymer 80 and the fiber reinforcement 76 entrained in the polymer 80. In some applications, it may be possible to temporarily interrupt feeding of the fiber reinforcement 76 in order to deposit beads 44 that are purely polymer 80 (devoid of fiber reinforcements) in order to form layers 22 that do not contain a reinforcement.

Attention is now directed to FIG. 5 which broadly illustrates a deposition fabrication method employing an end effector 20 of the type described above. Beginning at 54, a pressurized stream of a polymer 80 is established through a tube 68 which may be a capillary tube. The pressurized stream of the polymer 80 may be established by establishing a pressure differential between the polymer inlet 69a (FIG. 2) and the downstream end 68b of the capillary tube 68. At 56, a fiber reinforcement 76 is entrained within the pressurized polymer stream. In some embodiments, the method may optionally include heating the fiber reinforcement 76 before it is entrained in the pressurized stream of the polymer 80. At 58, a bead 44 of the polymer 80 having the fiber reinforcement 76 entrained therein is deposited from the tube onto a substrate 23. The pressurized stream of the polymer 80 may be established by supplying the polymer 80 to the upstream end 68a of the capillary tube 68 at a pressure P_1 that is higher than the pressure P_a at which the polymer exists the downstream end 68b of the capillary tube 68 and is deposited from the material deposition end 72.

FIG. 6 broadly illustrates a method of fabricating a composite part 26 by the additive manufacturing technique

previously described. At 60, a deposition head 40 is rastered over a substrate 23. At 62, features of the composite part 26 are additively formed by extruding a polymer 80 having an entrained continuous fiber reinforcement 76 from the deposition head 40 onto the substrate 23. Extrusion of the polymer 80 along with the entrained continuous fiber reinforcement 76 may be achieved by flowing a pressurized stream of the polymer 80 through a capillary tube 68 generated by a pressure differential $P_1 - P_a$ between an upstream end 68a and a downstream end 68b of the capillary tube 68.

In some applications, in order to increase fabrication speed, it may be necessary or desirable to employ an end effector 20 having more than a single deposition head 40. Referring to FIG. 7, a plurality of the deposition heads 40 may be ganged together in an array 88 on a single end effector 20 (FIG. 1). Each of the deposition heads 40 may include an extrusion nozzle 42 from which a bead (not shown) of fiber reinforced polymer may be deposited onto a substrate 23 (FIG. 1) to additively form features of the part.

Embodiments of the disclosure may find use in a variety of potential applications, particularly in the transportation industry, including for example, aerospace, marine, automotive applications and other application where fiber reinforced polymer parts may be used. Thus, referring now to FIGS. 8 and 9, embodiments of the disclosure may be used in the context of an aircraft manufacturing and service method 90 as shown in FIG. 8 and an aircraft 92 as shown in FIG. 9. Aircraft applications of the disclosed embodiments may include, for example, without limitation, prototype components, low production run parts and reinforced structures that may be difficult or costly to manufacture using conventional processes. During pre-production, exemplary method 90 may include specification and design 94 of the aircraft 92 and material procurement 96. During production, component and subassembly manufacturing 98 and system integration 100 of the aircraft 92 takes place. During component and subassembly manufacturing 98, the disclosed method and apparatus may be employed to produce components or subassemblies that are then integrated as part of the system integration 100. Moreover, the embodiments may be used to produce components that enable other components to be assembled together and/or integrated. Thereafter, the aircraft 92 may go through certification and delivery 102 in order to be placed in service 104. While in service 104 by a customer, the aircraft 92 is scheduled for routine maintenance and service 106, which may also include modification, reconfiguration, refurbishment, and so on. The disclosed embodiments may be used to fabricate parts or components that are used to repair or replace components as part of the maintenance and service 106.

Each of the processes of method 90 may be performed or carried out by a system integrator, a third party, and/or an operator (e.g., a customer). For the purposes of this description, a system integrator may include without limitation any number of aircraft manufacturers and major-system subcontractors; a third party may include without limitation any number of vendors, subcontractors, and suppliers; and an operator may be an airline, leasing company, military entity, service organization, and so on.

As shown in FIG. 9, the aircraft 92 produced by exemplary method 90 may include an airframe 108 with a plurality of systems 110 and an interior 112. Examples of high-level systems 110 include one or more of a propulsion system 114, an electrical system 116, a hydraulic system 122 and an environmental system 120. Any number of other systems may be included. Although an aerospace example is

shown, the principles of the disclosure may be applied to other industries, such as the marine and automotive industries. The disclosed embodiments may be employed to fabricate custom-designed, prototype or low production run fiber reinforced polymer components or parts used in the airframe **108**, any of the systems **110** or the interior **112**.

Systems and methods embodied herein may be employed during any one or more of the stages of the production and service method **90**. For example, components or subassemblies corresponding to production process **98** may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft **92** is in service. Also, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during the production stages **98** and **100**, for example, by substantially expediting assembly of or reducing the cost of an aircraft **92**. Similarly, one or more of apparatus embodiments, method embodiments, or a combination thereof may be utilized while the aircraft **92** is in service, for example and without limitation, to maintenance and service **106**.

As used herein, the phrase “at least one of”, when used with a list of items, means different combinations of one or more of the listed items may be used and only one of each item in the list may be needed. For example, “at least one of item A, item B, and item C” may include, without limitation, item A, item A and item B, or item B. This example also may include item A, item B, and item C or item B and item C. The item may be a particular object, thing, or a category. In other words, at least one of means any combination items and number of items may be used from the list but not all of the items in the list are required.

The description of the different illustrative embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different advantages as compared to other illustrative embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. An end effector for performing deposition of a fiber reinforced polymer, comprising:

a supply of a continuous fiber reinforcement;
a supply of a flowable polymer; and
a deposition head having:

a material supply end configured to receive the continuous fiber reinforcement,
a deposition end configured to deposit a bead of the polymer having the continuous fiber reinforcement entrained therein,
a convergence region,
a capillary tube extending from the convergence region to the deposition end of the deposition head,
a guide tube extending from the material supply end of the deposition head to the convergence region and coaxially aligned with the capillary tube,
a polymer inlet, and
a polymer passageway extending from the polymer inlet to the convergence region;

wherein the continuous fiber reinforcement extends from the material supply end of the deposition head through the guide tube and the convergence region and into the

capillary tube and is loosely fed into the guide tube at the material supply end of the deposition head such that the continuous fiber reinforcement is not forced into the guide tube and is not placed in any substantial amount of compression at the material supply end of the deposition head; and

wherein the supply of flowable polymer is connected to the polymer inlet to establish a pressurized flow of the polymer through the polymer passageway and the convergence region and into the capillary tube to draw the continuous fiber reinforcement into and through the capillary tube where the continuous fiber reinforcement becomes entrained in the polymer.

2. The end effector of claim **1**, wherein the deposition head includes:

an entrainment barrel including the convergence region in which the continuous fiber reinforcement and the flowable polymer converge.

3. The end effector of claim **2**, wherein the entrainment barrel further includes an extrusion die coupled with the deposition end.

4. The end effector of claim **2**, wherein the entrainment barrel further includes the capillary tube coupled with the convergence region and configured to entrain the continuous fiber reinforcement in the polymer.

5. The end effector of claim **4**, wherein:

the capillary tube includes an upstream end coupled with the convergence region and a downstream end configured to extrude the polymer having the continuous fiber reinforcement entrained therein.

6. The end effector of claim **2**, further comprising:
a heater for heating the entrainment barrel, the heater including at least one heating coil having a plurality of coil turns that vary in number along a length of the entrainment barrel.

7. The end effector of claim **2** further comprising:
a cutter disposed to cut the bead of the polymer.

8. The end effector of claim **7**, wherein the cutter is selected from the group consisting of: a laser, an ultrasonic knife, and a guillotine blade.

9. The end effector of claim **2** further comprising:
a controller configured to control operation of the end effector.

10. The end effector of claim **2** further comprising:
a manipulator attached to the deposition head and configured to manipulate the deposition head.

11. The end effector of claim **10**, wherein the manipulator rasters the end effector over a platform to deposit the bead on the platform.

12. The end effector of claim **2** further comprising:
a manipulator attached to the deposition head and configured to manipulate the deposition head and to raster the end effector over a platform to deposit the bead on the platform; and
a controller configured to control operation of the end effector and of the manipulator.

13. The end effector of claim **12** further comprising:
a storage medium storing computer assisted design (CAD) files usable by the controller to control deposition of the bead.

14. The end effector of claim **13**, wherein the storage medium further comprises program code for converting the CAD files to stereolithography (STL) files defining surfaces of a part to be built on the platform.

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15. The end effector of claim 14, wherein the storage medium further comprises program code comprising build programs which are used to control operation of the manipulator and the controller.

16. The end effector of claim 2 further comprising a heater and a controller, and wherein:

the supply of continuous fiber reinforcement has a first melt temperature;

the flowable polymer has a second melt temperature that is less than the first melt temperature such that when entrainment is performed, the controller is configured to operate the heater to heat the supply of continuous fiber reinforcement and the flowable polymer to a third temperature that is above the first melt temperature but below the second melt temperature.

17. The end effector of claim 16, wherein the deposition head comprises:

the guide tube being disposed inside an annular inlet of the entrainment barrel surrounding the guide tube, wherein the guide tube ends at an entrance to the capillary tube disposed inside the entrainment barrel.

18. An end effector for performing deposition of a fiber reinforced polymer, comprising:

a supply of a continuous fiber reinforcement;

a supply of a flowable polymer; and

a plurality of deposition heads ganged together in an array, wherein each of the plurality of deposition heads comprises:

a material supply end configured to receive the continuous fiber reinforcement,

a deposition end configured to deposit a bead of the polymer having the continuous fiber reinforcement entrained therein,

a convergence region,

a capillary tube extending from the convergence region to the deposition end of the deposition head,

a guide tube extending from the material supply end of the deposition head to the convergence region and coaxially aligned with the capillary tube,

a polymer inlet, and

a polymer passageway extending from the polymer inlet to the convergence region,

wherein the continuous fiber reinforcement extends from the material supply end of the deposition head through the guide tube and the convergence region and into the capillary tube and is loosely fed into the guide tube at the material supply end of the deposition head such that the continuous fiber reinforcement is not forced into the guide tube and is not placed in any substantial amount of compression at the material supply end of the deposition head, and wherein the supply of flowable polymer is connected to the polymer inlet to establish a pressurized flow of the polymer through the polymer passageway and

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the convergence region and into the capillary tube to draw the continuous fiber reinforcement into and through the capillary tube where the continuous fiber reinforcement becomes entrained in the polymer.

19. The end effector of claim 18 further comprising a heater and a controller, and wherein:

each of the plurality of deposition heads comprises the guide tube, the guide tube being disposed inside an annular inlet of an entrainment barrel surrounding the guide tube;

wherein the guide tube ends at an entrance to the capillary tube disposed inside the entrainment barrel.

20. A method for performing deposition of a fiber reinforced polymer, comprising:

providing a continuous fiber reinforcement from a supply of the continuous fiber reinforcement and a polymer from a supply of flowable polymer to a deposition head, wherein the deposition head comprises:

a material supply end configured to receive the continuous fiber reinforcement,

a deposition end configured to deposit a bead of the polymer having the continuous fiber reinforcement entrained therein,

a convergence region,

a capillary tube extending from the convergence region to the deposition end of the deposition head,

a guide tube extending from the material supply end of the deposition head to the convergence region and coaxially aligned with the capillary tube,

a polymer inlet, wherein the supply of flowable polymer is connected to the polymer inlet, and

a polymer passageway extending from the polymer inlet to the convergence region;

loosely feeding the continuous fiber reinforcement into the guide tube at the material supply end of the deposition head such that the continuous fiber reinforcement is not forced into the guide tube and is not placed in any substantial amount of compression at the material supply end of the deposition head;

extending the continuous fiber reinforcement from the material supply end of the deposition head through the guide tube and the convergence region and into the capillary tube;

establishing a pressurized flow of the polymer from the polymer inlet through the polymer passageway and the convergence region and into the capillary tube to draw the continuous fiber reinforcement into and through the capillary tube where the continuous fiber reinforcement becomes entrained in the polymer; and

depositing a bead of the polymer having the continuous fiber reinforcement entrained therein from the deposition end of the deposition head.

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